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Physical and mechanical properties of lightweight concrete with the incorporation of waste disposal polyurethane foam as coarse aggregate

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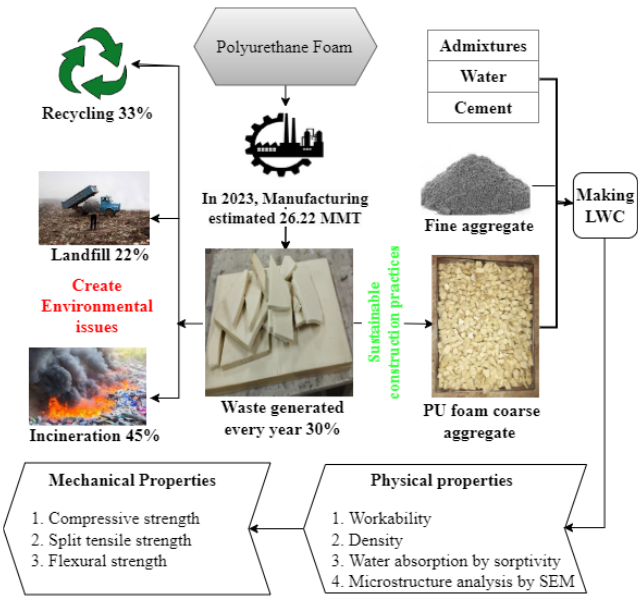
Graphical abstract



Abstract

Industrial waste in engineered concrete mixes is an enormous step towards sustainable development. Polyurethane foam waste (PUFW) is mainly generated by the refrigeration, automobile, and construction industries. Day by day, large amounts of PUFW are incinerated and disposed of in landfills, which not only affects the environment but also leads to the loss of land usage. On the other hand, with the improvement of financial benefits, environmental benefits, and structural style, the demand for lightweight concrete (LWC) is also increasing. This study investigated the incorporation of rigid PUFW as coarse aggregate in LWC. Various proportions of PUFW replacement by volume (40%, 50%, 60%, 70%, and 80%) were examined to formulate the LWC mixtures. The physical and mechanical properties of the LWC were tested and compared with conventional concrete. The results showed that the compressive strength reached more than 17 MPa when LWC was made with 40%, 50%, and 60% PUFW content, satisfying the compressive strength of structural LWC. At 70% PUFW content, the compressive strength was satisfactory for semi-load bearing strength, and at 80% PUFW content, it was suitable for insulation concrete. In all mix proportions, the density value was less than 2000 kg/m^3, which was satisfactory for LWC.

Keywords: Polyurethane foam waste, lightweight concrete, mechanical properties, physical properties, water absorption, microstructure analysis

Abbreviations

PUFW–Polyurethane foam waste; LWA–Lightweight aggregate; LWC–Lightweight concrete; NWA–Normal weight aggregate; W/CWater to cement ratio; MPU–Mix Polyurethane foam waste; SP–Superplasticizer; SEM–Scanning electron microscopy; ASTM–American society for testing and materials; ACI–American concrete institute; IS–Indian standard; ES - European standard; BS - British standard C; FA–Fine aggregate; CA–Coarse aggregate; MMT–Million metric ton;

1. Introduction

Millions of tons of Polyurethane foam waste (PUFW) are disposed of in landfills and incinerated annually. According to the latest Global Polyurethane Market Volume 2015–2030 recent report and analysis released by the Statista research department, in 2023, the global polyurethane foam market volume was estimated to be nearly 26.22 million metric tons (Statista Research Department 2023). The demand for polyurethane foam is 25% in the building industry, 20% in the automotive industry, 25% in the refrigeration industry, and 30% in the textile and other industries. Every year, around 30% of PUFW is generated from the estimated total market volume, of which only 33% is recycled, the remaining 45% is incinerated, and 22% is disposed of landfill (Data bridge market research 2022; Gómez-Rojo *et al.* 2019). Incinerating PUFW generates severe fire hazards, produces potentially toxic substances, and may contribute to smog, which has become a severe environmental issue (Kemona & Piotrowska 2020; Nikje *et al*. 2011). Landfilling with PUFW reduces the number of valuable sites available (Gadhave *et al*. 2019). PUFW is generated due to the destruction of insulation panels used in the construction industry, the manufacturing of leftover materials, scrapped car seats, and the end of their life cycle (Banik *et al*. 2023; Członka *et al*. 2018; Tantisattayakul *et al*. 2018). Recently, waste disposal on land has been banned in the Netherlands, New Zealand, Sweden, Denmark, and Switzerland. Currently, there are restrictions on the disposal of materials with a high carbon content in Germany and Australia (Yang *et al*. 2012). With a growing global awareness of environmental production and the concept of sustainable development, significant changes in environmental problems, and a developing need for clean and green earth, the demand for PU foam reuse is increasing.

Conversely, the demand for Lightweight Concrete (LWC) is increasing for financial benefits, reduced weight, improved thermal insulation, structural efficiency, sound insulation, reduced foundation cost, transportation and handling benefits, and environmental sustainability (Naveen Arasu A. *et al*. 2023; Satish Chandra 2002). Concrete is one of the most essential materials in the building industry. The past fifty years have experienced an increase in the demand for concrete due to the rate of population growth. There is a great need to construct more residential buildings and infrastructure. The demand for conventional materials used in concrete, such as cement and aggregate, increases continuously. Conventional building materials increase the cost of building a new house, add weight to the structure, and cause construction to take longer to finish (Saidani *et al*. 2022). Concrete development is beginning to take a more definite direction toward lightweight, environmentally friendly, and highly durable concrete due to the advancement of financial benefits and sustainable development goals (Bejan *et al*. 2020). LWC has recently emerged in the construction industry. It has many advantages over traditional concrete, including lower construction costs, reduced structure weight, reduced quantity of materials used, and the ability to complete work quickly. LWC structures reduce the weight by more than 20% (Kim *et al*. 2020). According to the American Concrete Institute (ACI), LWC has a compressive strength of at least 17 MPa and a density between 1350 and 1900 kg/m^3 (ACI 213R, 2014).The British Standard (BS) code calls for LWC with densities between 800 and 2000 kg/m^3 (BS EN: 206-1, 2013). According to the ASTM C09, semi-load-bearing lightweight concrete has a compressive strength of at least 15 MPa, and insulation concrete has a compressive strength of less than 10 MPa (ASTM Committee C09 on Concreate and Concrete Aggregates 2017). In recent years, researchers have carried out studies on the use of various waste by-products (construction industry waste, agriculture waste, miscellaneous and natural waste, quarrying dust waste, recycled plastic, hazardous waste, plastics and glass) as aggregates in cement concrete mixtures for sustainable development, recycling, and environmental production (Halahla *et al*. 2019; Junaid *et al*. 2022; Shanmuga Priya S & Padmanaban I 2023; Subashree Paramasivan & Thenmozhi Rajagopal 2023). This study uses waste disposal PUFW as coarse aggregate in cement concrete mixtures.

Few studies are available in the literature using PUFW as fine and coarse particles in cement concrete mixtures. However, more research is required to study and test the use of PUFW as a coarse particle in concrete mixtures. Ben Fraj *et al*. fully replaced coarse particles and reported that concrete produced using PUFW (8–20 mm) as coarse particles achieved a maximum compressive strength of 16 MPa with a density of 1791 kg/m^3 (Ben Fraj *et al*. 2010). Another research investigated 0–10 mm size of PUFW in the concrete mixture to develop compressive strength with less density and reported a compressive strength of 10.4 MPa and a density of 1583 kg/m^3 (Mounanga *et al*. 2008). Tomáš Dvorský 2016 used a new finely ground limestone instead of sand with a PUFW size of 4 to 8 mm in the concrete matrix and reported that the compressive strength was 2.79 MPa and the unit weight was 1040 kg/m^3. Furthermore, PUFW aggregate in the size range of 8–20 mm was used to develop the compressive strength of concrete and reached a maximum compressive strength of 8.5 MPa (Wang *et al*. 2012). There are two main types of PUFW: flexible and rigid polyurethane foam. Flexible PU foams have excellent elasticity, flexibility, elongation, compressive strength, chemical stability and solvent resistance. Rigid polyurethane foams have significant qualities such as excellent mechanical performance, resistance, insulation and sound absorption capacity (Chris Defonseka 2013; Gama *et al*. 2018; Izarra *et al*. 2021; Shoaib Suleman 2014). All researchers used rigid PUFW with a maximum density of 60 kg/m^3, achieving a maximum compressive strength of 16 MPa with a density of 1791 kg/m^3. However, the ACI 213 states that LWC minimum compressive strength is 17 MPa (ACI 213R 2014). No research is available on developing PUFW in concrete with a compressive strength greater than 16 MPa. Additionally, no research has been conducted on other mechanical properties, such as flexural strength, split tensile strength, and water absorption. As a result, the main objective of this research was to construct PUFW as coarse particles in concrete with a more remarkable compressive strength than that developed in previous research studies. This present study used high-density rigid PUFW with a density of 160 kg/m^3, which has less porosity and less water absorption due to closed cell structures, which leads to better compressive strength. The effects of the physical and mechanical properties of LWC were investigated in addition to studying the other mechanical characteristics of the developed PUFW concrete mix. This article studied the utilization of waste disposal PU foam as a lightweight aggregate in cement concrete mixtures. An experimental investigation was carried out to assess the physical properties of PU foam lightweight concrete, including workability through a slump test, density, and water absorption via immersion and sorptivity tests. Additionally, mechanical properties such as compressive strength, flexural strength, and split tensile strength were evaluated. Furthermore, the microstructure analysis of the PU foam aggregate and PU foam aggregate concrete was also discussed.

1.1. Research significance

Utilization of waste disposal PUFW in cement concrete mixtures is important because it successfully diverts waste from landfills and reduces demand for traditional materials like aggregate and sand, thereby preserving natural resources and reducing the environmental effects of extraction and processing. Incorporating waste disposal PUFW into concrete mixtures can generate financial savings by reducing material prices. Because PUFW is a waste material, it is less expensive than other materials. Furthermore, lower transportation and disposal costs can lead to significant savings in waste management. Waste PU foam is a lightweight material when compared to normal aggregates. Replacing a portion of normal aggregates with PU foam waste reduces total concrete density by more than 50%. This density reduction provides lighter concrete, which reduces structural loads in buildings and infrastructure. It is useful when weight reduction, such as floors and roofing, is desired. Utilization of waste polyurethane foam in concrete not only handles waste management issues but also makes a beneficial impact on environmental sustainability by conserving resources, saving energy, lowering carbon emissions, increasing building efficiency, and fostering the ideas of the circular economy.

2. Materials and methods

2.1. Cement

53-grade Ordinary Portland cement, confirming the Indian Standard, has been used as a binding material for this research (IS 269:2015, 2015). The standard consistency of cement was determined as per IS 4031 and was used to determine the initial and final setting times (IS 4031:1988 (Part-4), 1988; IS 4031:1988 (Part-5), 1988). The physical and chemical properties of cement are shown in Table 1.

Table 1. Physical and chemical properties of cement

Physical Properties		Chemical Properties	
Initial setting time	70 minutes	Silica (SiO2)	21.00
Final setting time	360 minutes	Alumina (Al2O3)	5.20
Specific gravity	3. 15	Iron Oxide (Fe2O3)	2.20
Normal consistency	30.5%	Calcium Oxide (CaO)	67. 39
Fineness modulus	1.66%	Magnesium Oxide (MgO)	1.81
Compressive strength	56 MPa	Sodium oxide (Na2O)	2. 10
-	-	Potassium oxide (K2 O)	0.20
-	-	Loss on ignition	0. 10

Table 2. Physical properties of PUFW

Property	Grain size (mm)	Density as waste panel (kg/m³)	Density as coarse particle (kg/m³)	Water absorption 24 hours (%)	Specific gravity
PUFW as coarse particles	4.75 – 20	200	160	13.5	0.32

2.2. Aggregate

Manufacturing sand with a maximum size of 4.75 mm was used as fine aggregate, confirming zone II as per IS 383. The specific gravity test of the fine aggregate was conducted as per the IS code, and the value obtained was 2.65 (IS 2386: Part III, 2016). Graded crushed granite aggregates with a maximum nominal size of 20 mm and more than 4.75 mm were confirmed to be used as coarse aggregate in the concrete mixes, and the specific gravity of coarse aggregate was 2.75 (IS 2386: Part III, 2016).

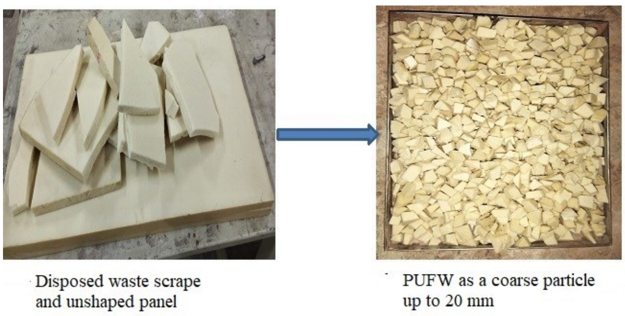


Figure 1. PUFW as coarse particles

2.3. Superplasticizer

A polycarboxylate-based superplasticizer was added to the concrete to improve workability by lowering the water-to-cement ratio. In its liquid form, it has a density of 1050 kg/m^3 and a dry content of 21%.

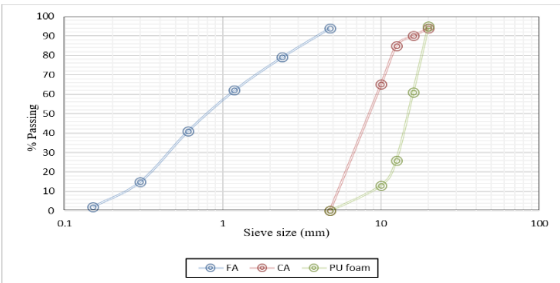


Figure 2. Particle size distribution curve of FA, CA and PUFW

2.4. Polyurethane foam waste

PUFW were taken from manufacturing insulation panels for the building industry at Prasanna Sri Energy System and Services, Chennai. A manufacturer provided waste-disposed panels, then converted to coarse particles in the laboratory, as shown in Figure.1. According to the standard code (IS 2386:2016 (Part III), 2002), the results for the density and water absorption of PUFW as coarse particles are presented in Table 2. The particle size distribution of PUFW (4.75-20 mm) was measured according to the standard (IS 2386:2016 (part 1), 2016), and the results are shown in Figure.2.

2.5. Design and preparation of specimen

In this study, various volume replacement mix proportions were prepared as per IS code (IS 10262:2019)(IS 10262:2019). The maximum size of PUFW was 20 mm, and water-cement ratios were 0.4 and 0.43, respectively. In addition, the superplasticizer was 1% and 1.5% by weight of cement. The reference mix (MPU0) was considered conventional concrete among these various mix proportions. Five LWC with 40%, 50%, 60%, 70%, and 80% of PUFW (MPU40, MPU50, MPU60, MPU70, and MPU80) were designed. In these mix proportions, PU foam waste replaced the normal coarse aggregate dosage in volume, as shown in Table 3.

Table 3. Mix proportions

Mix code	Mix proportions (kg/m^3)						PU foam replacement level by CA volume (%)	W/c ratio
	Cement	Water	Sand	Normal aggregate	PU foam aggregate	SP		
MPU0	340	148	842	1145	-	3.4	-	0.43
MPU40	340	148	842	687	58	3.4	40	0.43
MPU50	340	148	842	573	72	3.4	50	0.43
MPU60	340	136	842	458	81	5.1	60	0.40
MPU70	340	136	842	343	105	5.1	70	0.40
MPU80	340	136	842	229	122	5.1	80	0.40

2.6. Mixing and casting

The machine mix drum was filled with cement, fine aggregates, coarse aggregate, and PUFW for dry mix and mixed for 5–7 minutes. Water and superplasticizer were gradually added to the dry mixture and mixed for another 10–15 minutes. Prepared fresh LWC with different mix proportions. Then, the freshly prepared concrete was filled with the steel cube, cylinder, and prism moulds as per IS 516 for compressive strength, split tensile strength, and flexural strength (IS 516:2021 (Part 1/Sec 1), 2021). A minimum of 3 specimens were cast for every mix proportions, as shown in Figure 3. Casting was carried out, and the concrete was filled to mould in three layers. Each layer was compacted with a tamping rod to remove the trapped air. Cast specimens were cured in a water tank for 28 days after 24 hours of de-moulding for mechanical testing.

Figure 3. Casting of cube, cylinder and prism

2.7. Methods

2.7.1. Workability

To prevent the PUFW lightweight aggregates from floating during mixing, they soaked them in water for 24 hours before mixing. Ben Fraj and Mounanga investigated whether PUFW with a water saturation condition in concrete gives better Workability (Ben Fraj *et al*. 2010; Mounanga *et al*. 2008). The dosage of SP for adjusting the workability of concrete is between 1% and 1.5% of the cement weight. According to IS 456, a slump value of 50–100 mm was considered (IS 456:2000). They were mixed in vertical shaft mixers according to particle size, ranging from large to small. Water was added gradually after uniform mixing. The fresh LWC slump was evaluated and corrected with SP after a 3–5 minute mixing time.

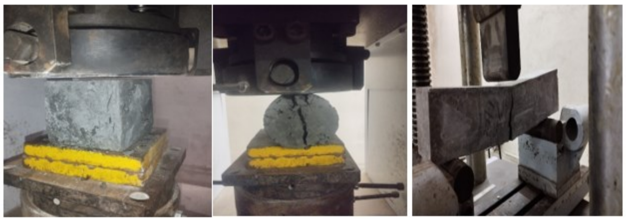


Figure 4. Testing of cube, cylinder and prism

2.7.2. Mechanical strength

Concrete cubes with dimensions of 100 mm x 100 mm x 100 mm were cast and cured for 28 days. After this period, they were subjected to a compression test using equipment capable of handling up to 2000 kN. The test aimed to evaluate the compressive strength of LWC for all specimens. The loading rate was 13.7 N/mm^2/min, and the mixtures were prepared according to IS 516 standards. (IS 516:2021 (Part 1/Sec 1), 2021). The cube specimen was placed in the centre of the machine, and a direct compressive load was applied until the specimen failed. After recording the maximum load at failure, the maximum load was divided by the specimen's cross-section area to find the compressive strength. Cylindrical specimens of 150 mm in diameter and 300 mm in height were used and tested after 28 day curing period to determine the split tensile strength of concrete for all the specimens at the loading rate of 1.4 N/mm^2/min as per IS 516 (IS 516:2021 (Part 1/Sec 1), 2021). The cylinder specimen was placed horizontally in the machine centre, and a direct load was applied until the specimen failed, and the maximum load was recorded. To determine flexural strength, 100mm x 100mm x 500mm prisms were cast and tested after a 28-day curing period. The loading rate was 0.7 N/mm^2/min, as per IS 516(IS 516:2021 (Part 1/Sec 1), 2021). A three-point loading test setup was considered to test flexural strength. Figure. 4 represents the testing of the cube, cylinder, and prism.

2.7.3. Water absorption

The water absorption by immersion and sorptivity of PU foam LWC mixes were also investigated for their durability properties. The size of the specimen used for the water absorption by sorptivity tests is 100 mm in diameter and 50 mm in thickness. A test was conducted after a 28-day curing period, and the testing method was carried out as per ASTM standards (ASTM C 1585, 2018). The study tested water absorption through the sorptivity of various mix proportions after 28 days of curing. Epoxy resin was applied to the sides of specimens to test sorptivity. Before testing, the specimens' masses were recorded. Then, the specimens were submerged in water to a depth of 5 mm, as shown in Figure. 5, maintaining the water level 1 to 3 mm above the top of the support device for the duration of the tests.

Figure 5. Water absorption by sorptivity test

3. Physical properties results and discussions

3.1. Workability

The slump test is a widely used method for measuring the workability of concrete. It enables the assessment of its consistency and determines its ability to flow and fill the formwork (Aïssoun *et al*. 2016; Chen & Liu 2008). It is very beneficial to find out the correct mixing proportions for concrete (Neville 1987). The incorporation of waste PU foam in concrete enhances its workability by increasing its fluidity and flowability. Ben Fraj reported that saturated PUFW as coarse aggregate in concrete had better Workability (Ben Fraj *et al*. 2010). Consequently, the present study used water-saturated PUFW as aggregate to increase the workability of concrete. The more SP was added to maintain the same amount of slump in the LWC as the workability decreased. According to the IS standard (IS456:2000) code, the slump test results and the amount of SP used in each proportion were recorded, as shown in Figure 6. Comparing the mix proportions, the PUFW increases with slump value decreases because PUFW with high porosity absorbs more water. Figure 6 shows that as the PU foam volume increases, the SP content also increases. MPU0 and MPU50 have the same dosage of SP, but the slump value decreases gradually. Similarly, the proportions between MPU60 and MPU80 also have the same dosage of SP, but the slump value decreases gradually. The irregular shape of PUFW leads to greater surface friction, reducing slurry flowability.

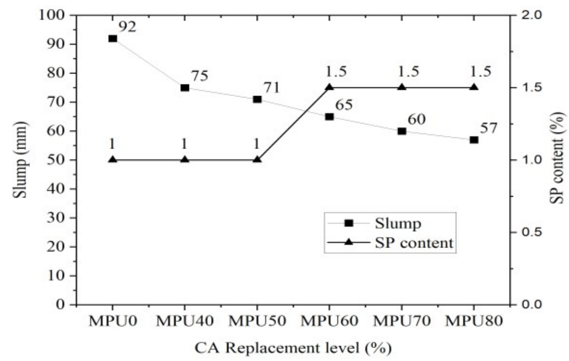


Figure 6. Variation of slump and SP dosage for the different mix proportions

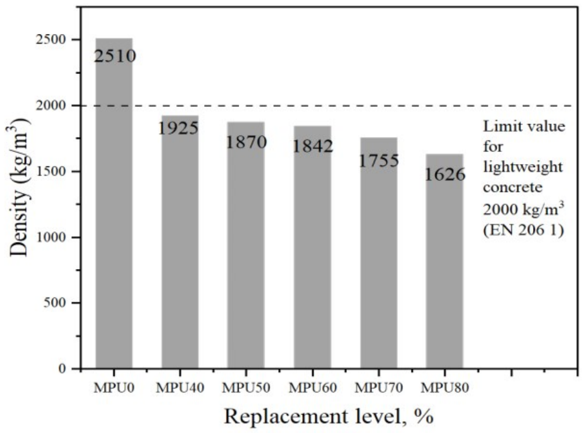


Figure 7. The density of each mix proportions

3.2. Density

The hardened density of the cement concrete plays an essential role in the dead load of the structures. Concrete density is important, particularly for LWC (Bejan *et al*. 2020; Bengin M A Herki; J. L. Clarke 1993; Satish Chandra 2002). In all PUFW mix proportions, the density of LWC was less than 2000 kg/m^3, and the limit value for LWC was satisfied as per BS code (BS EN: 206-1, 2013). The addition of PUFW results in a lower mix proportion density, as shown in Figure. 7. The results of the figure show that the density of the LWC with 80% PU foam content was 1626 kg/m^3, and it was observed to have almost reduced by 35.21% of its self-weight than conventional concrete. Lightweight concrete has a 23.3% density decrease at a PUFW content of 0 to 40%, a 2.85% density decrease at a PUFW content of 40% to 50%, a 1.49% density decrease at a PUFW content of 50 to 60%, and a 4.7% density decrease at a PUFW content of 60 to 70%. Previous literature studies used less-density rigid PUFW as coarse and fine particles with various mix proportions in concrete and observed that the density ranged between 1040 and 1791 kg/m^3. However, this study used high-density rigid PUFW with various mix proportions and observed a density between 1626 and 1925 kg/m^3. However, the density of MPU40 cementitious proportions increased by 7.5% compared to previous literature because high-density rigid PUFW has less porosity and a closed cell structure compared to other types of flexible PUFW and rigid PUFW. PU foam has a less density than conventional coarse aggregates used in concrete, resulting in lightweight concrete that is more workable due to its reduced density. This less density facilitates easier transportation, pumping, and installation.

3.3. Water absorption by sorptivity test

According to ASTM C1585, water absorption by sorptivity of various mix proportions was tested, ranging from 1 minute to 8 days (ASTM C 1585, 2018). A cylindrical specimen with a diameter of 100 mm and a thickness of 50 mm was prepared. As observed in Figure. 8, the water absorption by sorptivity of the LWC increases with an increase in PUFW content in all mix proportions during the initial and secondary absorption stages. This behaviour is also explained by the PUFW absorbing a higher amount of water than that of conventional coarse aggregate, which also explains the LWC increased water absorption by sorptivity when more PUFW was used instead of conventional coarse aggregate. But compared to previous literature, this study used high-density rigid PUFW instead of flexible and rigid PUFW, which can lead to decreased water absorption by sorptivity because high-density rigid PU foam has less porosity with closed cell structure when compared to other types of PUFW. When the PUFW content reaches 60% and 80%, the effect on the water absorption of LWC on the 8th day increases by 50.42% and 86.4% compared to conventional concrete.

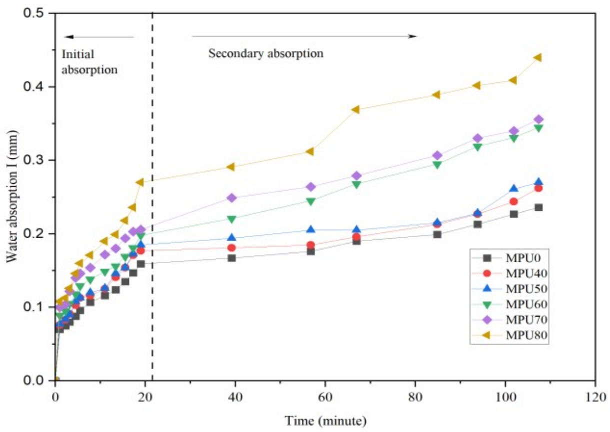


Figure 8. Water absorption by sorptivity test

3.4. Water absorption by immersion

The water absorption values by immersion were obtained for the various mix proportions, as shown in Figure 9. It was observed that the water absorption increased with the addition of PUFW coarse particles. The water absorption of LWC by immersion increased by 26.21% when the PUFW was 40%. However, there are not many differences between MPU40 and MPU50. When the PUFW content reached 80%, water absorption by immersion was 67.47% greater than MPU0. It has been observed that PUFW has a higher water absorption capacity than normal aggregate due to high porous nature and large surface area. The concrete with a higher content of PUFW as coarse aggregate replacement has a higher water absorption capacity. In this study, high-density rigid PU foam was used as a coarse particle; it has less porosity, and its closed-cell structure leads to less water absorption capacity when compared to rigid and flexible PUFW.

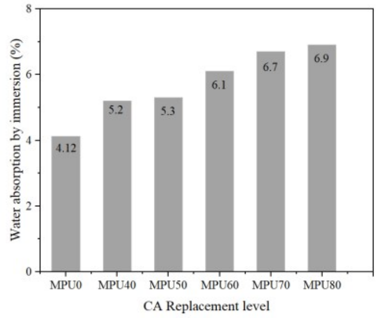


Figure 9. Water absorption by immersion

3.5. Microstructure characterization

Microstructure analysis plays a crucial role in examining the pore structure of lightweight concrete, including pore size, distribution, and connectivity. Additionally, by analyzing the bond strength and identify potential weak points within the concrete. The minor pieces of PUFW and LWC samples were taken from the central part of the 28-days-cured specimens to prepare the sample for Scanning Electron Microscope (SEM) analysis (Zhang & Gjørv, 1990). SEM is a microscope that can capture detailed images of small particles. It uses electronic technology to produce high-resolution photographs of the particle surface (Mehta 2014). The photos that were taken help investigate the surface materials morphology. SEM images were collected at different magnification ranges to investigate the size and shape of the PUFW and LWC particles, as shown in Figure 10. The presence of pores in the cells in this particular case, PU foam layers, and metal impurities are typical of this foam, as shown in Figure 10 (a) and 10 (b).

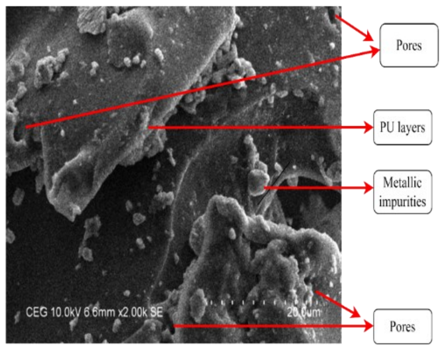


Figure 10 (a). SEM micrograph for PUFW

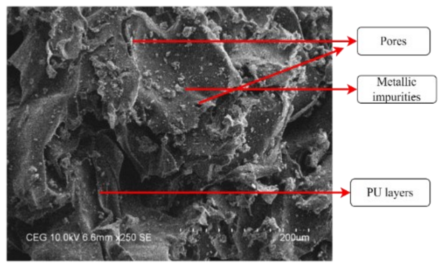


Figure 10 (b). SEM micrograph for PUFW

Figure 11 SEM images illustrate good adhesion between PU foam aggregate and cementitious matrix because the waste PU foam aggregate surface is high porosity and not smooth. It was reported that PUFW has a high degree of flexibility, which gives the mixture good crack resistance, allowing it to absorb minor structural movements without breaking up while remaining adhered to the support structure.

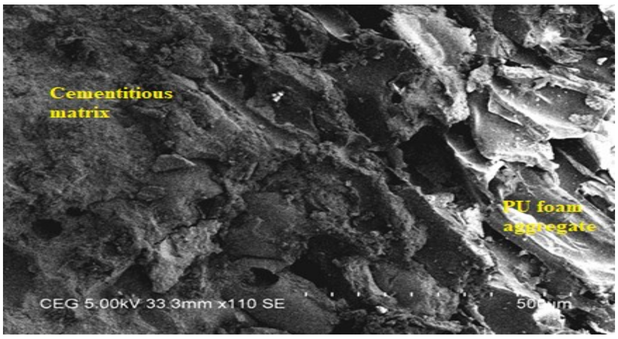


Figure 11. SEM micrograph for LWC with PUFW

4. Mechanical properties results and discussions

4.1. Compressive strength

According to the ACI standard, the structural LWC has a minimum 28-day compressive strength of 17 MPa (ACI 213R 2014). The ASTM C09 standard states that the semi-load-bearing LWC has a compressive strength of around 15 MPa, and the compressive strength of insulation concrete is less than 10 MPa. In this study, the compressive strength values of LWC mixes range from 9.8 to 21.7 MPa. Figure. 12 shows that the compressive strength of LWC with 40% PUFW was 27.18% lower than conventional concrete. Reduced compressive strength was 35.94% when the PUFW content was raised from 40% to 70%. At 80% PUFW, the compressive strength of the LWC was reduced to 9.8 MPa, the lowest value of all mix proportions and 67.11% lower than conventional concrete. Figure. 12 shows that the compressive strength decreased when coarse aggregate was replaced with high-density rigid PUFW due to high porous nature and low mechanical properties. Numerous studies that have already investigated PUFW in concrete mixtures show that the compressive strength reached 16 MPa (Ben Fraj *et al*. 2010; Mounanga *et al*. 2008). Present studies show that the compressive strength increased by 35.62% at MPU40, 19.37% at MPU50, and 8.75% at MPU60 compared to the maximum compressive strength in the previous study. Increasing compressive strength is increased because high-density rigid PUFW has less porosity with closed cell structure, PU foam surface not smooth gives better bonding, and less water absorption compared to other types of PUFW, as shown in Table 4. The MPU40, MPU50, and MPU60 mix proportions achieved compressive strengths greater than 17 MPa, satisfying the minimum compressive strength for structural LWC as per ACI 213R. At MPU70 mix proportions, the compressive strength was 13.9 MPa, satisfying the semi-load bearing strength as per ASTM C09. At MPU80, the compressive strength was less than 10 MPa, and it was used for insulation concrete and filler material as per ASTM C09.

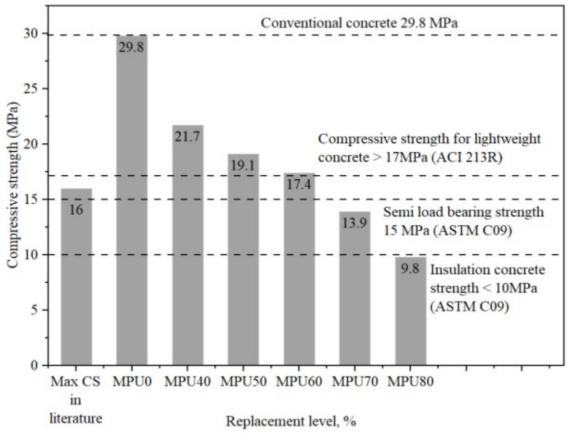


Figure 12. Compressive strength of each mix proportions

Table 4. Comparison of compressive strength and density of LWC developed in the Present study and that reported in the literature

Reference	PUFW as aggregate				LWC	
	Type	Density (kg/m³)	Size (mm)	Replacement level by volume	Density (kg/m³)	Compressive strength (MPa)
Present study	High density rigid	160	4.75 – 20	40%, 50%, 60%, 70% and 80% of CA	1626-1925	9.8-21.7
(Ben Fraj *et al*. 2010)	Rigid	45	8-20	35% and 45% of concrete	1656-1791	8-16
(Mounanga *et al*. 2008)	Rigid	45	0-10	13%, 17%, 22%, 28% and 34% of concrete	1100-1679	1.4-10.4
(Tomáš Dvorský 2016)	Semi-rigid	30-35	4-8	40% of the normal aggregate	1040-1100	2.33-2.79
(Wang *et al*. 2012)	Rigid	45	8-20	10-50% of normal coarse aggregate	-	5.3-8.5
(V. Václavík *et al.* 2012)	Rigid	30-60	0-6	40-100% of FA	1000-1200	5.1-9

The conventional concrete mix has a hardened density of 2510 kg/m³, which results in a compressive strength of 29.8 MPa. However, when 40% of PUFW was used as coarse particles, the density of LWC decreased by 23.3%, which decreased the compressive strength by 27.18%. Ben Fraj *et al*. investigated that the PU foam lightweight concrete achieved a maximum compressive strength of 16 MPa with a density of 1791 kg/m³ (Ben Fraj *et al*. 2010). The current study found that the compressive strength increased by 35.62%, and density slightly increased when 40% of PUFW. In all mix proportions containing PUFW, the density of LWC was less than 2000 kg/m³, satisfying the limit value for LWC as per EN 206 1(BS EN: 206-1, 2013). The reason for the increasing compressive strength with the required density was that high-density rigid PUFW has less water absorption due to its closed-cell structure.

Satutared PUFW in concrete has better absorption capacity, and the shape of PUFW was angular and rough in texture.

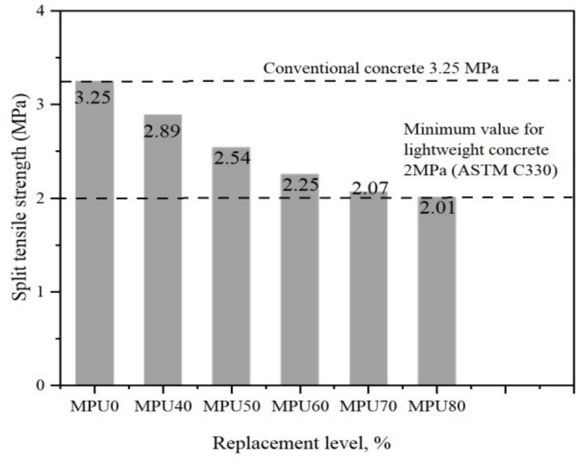


Figure 13. Split tensile strength of each mix proportions

4.2. Split tensile strength

According to the ASTM standard, the minimum splitting tensile strength for structural LWC must be 2 MPa (ASTM C330/C330M–09, 2017). Figure. 13 illustrates that all the produced mixes had splitting tensile strength values greater than 2.0 MPa. The conventional concrete had a splitting tensile strength of 3.25 MPa, and the LWC measured for all types of mixing conditions ranged from 2.01 MPa to 2.89 MPa, as shown in Figure. 13. At 28 days, the split tensile strength of LWC decreased by 3-45% than conventional concrete. Several studies have previously shown that using semi-rigid and rigid PUFW as coarse and fine particles in concrete mixtures causes a very high decrease in the mechanical properties of concrete (Tomáš Dvorský 2016). This study used higher-density PUFW as a coarse particle, resulting in increased mechanical properties. Mounanga reported that the PU foam aggregates angular shape and irregular surface resulted in good adhesion with the cement paste.(Mounanga *et al*. 2008). On the contrary, all mix proportions almost satisfied the criteria of structural LWC as per ASTM C 330.

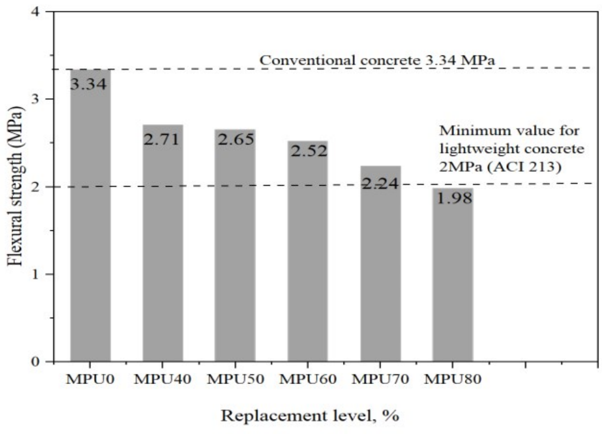


Figure 14. Flexural strength of each mix proportions

4.3. Flexural strength

The conventional concrete flexural strength was 3.34 MPa, while LWC with all mix proportions ranged from 1.98 to 2.71 MPa. Figure 14 presents a decrease in the flexural strength of LWC as higher-density PUFW is added, compared to conventional concrete. The flexural strength of LWC with MPU40, MPU50, MPU60, MPU70, and MPU80 decreased by 16.61%, 18.46%, 22.4%, 31.07%, and 39.07%, respectively, when compared to conventional concrete. The decreased flexural strength may be attributed to absorbing a large amount of water, high porosity, weak physical and mechanical properties of PU foam waste. However, the flexural strength increased in LWC by incorporating higher-density rigid PUFW than low-density rigid PU foam and flexible foam.

The reason for increased flexural strength was that higher-density PUFW has a less porous and not smooth surface, which leads to good adhesion and better flexural strength. In all mix proportions, results showed at least greater than 2 MPa and satisfied the minimum flexural strength for structural LWC as per ACI standard. (ACI 213R, 2014).

5. Conclusions

This study investigated the effect of various mix proportions on the physical and mechanical properties of LWC with the addition of PUFW. After analyzing the experimental results, we can draw the following conclusions:

- The waste PUFW as aggregate in the concrete mixture is a sustainable construction practice, thus providing an environmentally friendly solution for PUFW disposal and traditional aggregate manufacturing industries.
- Around 45% of waste PU foam is incinerated. Using waste PU foam in concrete instead of incineration can help reduce fire hazards, smog, and environmental issues.
- Incorporating waste PU foam into a concrete mixture helps reduce the amount of PU foam waste disposed of in landfills. Reusing the disposal of PU foam waste into concrete mixtures can reduce material costs, reduce structural load, improve workability, and contribute to sustainable construction practices.
- The slump value decreased when PUFW content was used as a partial replacement for coarse aggregate. However, it maintained the slump value of 50–100 mm due to PU foam used in a water-saturated condition, and SP dosage increased when increasing PUFW.
- The compressive strength attained more than 17 MPa per ACI 213 when LWC was made with 40%, 50%, and 60% of PUFW content. Compressive strength increased by almost 41% when compared to previous studies due to the high density of PUFW used in this study. It has less porosity, less water absorption, and a closed-cell structure. Also, PUFW was angular and cubical in

shape and rough in texture, achieving good bonding and better mechanical strength. At 70% PUFW content for coarse aggregate, the compressive strength value was 13.9 MPa, which is satisfied for semi-load bearing strength. At 80% PUFW content, the compressive strength value was less than 10 MPa for thermal insulation and filler material.

- The split tensile strength and flexural strength decreased with an increase in the quantity of PUFW content due to less porosity and high water absorption compared to conventional coarse aggregate. However, split tensile strength achieved more than 2 MPa in all mix proportions and satisfied ASTM C330.
- In all mix proportions, the dry density of the lightweight concrete with PU foam content (40–80%) was less than 2000 kg/m^3 and satisfied as per EN 206 and ACI 213R.
- Replacing conventional coarse aggregate with PUFW increased water absorption. The higher water absorption can be explained due to its high porous structure. During the initial and secondary absorption periods, as the PUFW content increases, the water absorption by the sorptivity of the LWC also increases.
- The SEM images identified porosity, polyurethane foam layers, and metallic impurities. The LWC showed good adhesion between the PUFW and the cementitious matrix because the surface of the waste PUFW was angular in shape, rough in texture and not smooth surface.

6. Recommendations for future research

- Adding fibres like steel, basalt, and glass fibres to cement concrete is recommended to increase its mechanical properties.
- PUFW aggregate is a suitable material for lightweight structures with good characteristics. It is recommended that PUFW as aggregate in concrete studied for different types of LWC structural precast elements.
- Further exploration is needed in the practical application and structural design considerations of PUFW lightweight concrete structures.
- Research is required to investigate the fire behaviour of PUFW lightweight concrete. However, further studies are required to investigate non-destructive testing methods, toughness, and modulus of elasticity.

Author Contribution:

First author: Roobankumar R–Conceptualization, Manuscript composition.

Corresponding author: SenthilPandian M–Supervision, Reviewing and Editing.

Conflict of interest

The authors declare that they have no conflict of interest.

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